GAMMA-RAY BURSTS FROM NEUTRON STAR BINARIES

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We report on general relativistic hydrodynamic studies which indicate several new physical processes which may contribute to powering gamma-ray bursts in neutron star binaries. Relativistically driven compression, heating, and collapse of the individual stars can occur many seconds before inspiral and merger. This compression may produce a neutrino burst of $\sim 10^{53}$ ergs lasting several seconds. The associated thermal neutrino emission produces an $e^+ - e^-$ pair plasma by $\nu\bar{\nu}$ annihilation. We show first results of a simulated burst which produces $\sim 10^{51}$ erg in γ-rays. We also discuss a preliminary study of the evolution of the magnetic field lines attached to the fluid as the stars orbit. We show that the relativistically driven fluid motion might lead to the formation of extremely strong magnetic fields ($\sim 10^{17}$ gauss) in and around the stars which could affect to the formation and evolution of a gamma-ray burst.

It has been speculated for some time that inspiraling neutron stars could provide a power source for cosmological gamma-ray bursts. The rate of neutron star mergers (when integrated over the number of galaxies out to high redshift) could account for the observed GRB event rate. The possibility that at least some γ-ray bursts involve x-ray, optical, or radio counterparts and are of cosmological origin has recently received observational impetus.[1] Mg I absorption and [O II] emission lines along the line of sight from the GRB970508 optical transient imply [2] that at least one burst is at a redshift $Z \geq 0.835$. If the bursts are cosmological, however, they must entail a release of $\sim 10^{51}$ erg in γ-rays on a time scale $\sim$ seconds. Here we show preliminary calculations of a relativistically driven GRB which is consistent with all of these constraints.

Previous, Newtonian and post Newtonian studies [3] of the direct merger of two neutron stars have found that the neutrino emission time scales are so short that it would be difficult to drive a gamma-ray burst from this source. However, our numerical studies of the strong field relativistic hydrodynamics of close neutron star binaries in three spatial dimensions [4,5,6] have shown that neutron stars in a close binary can experience relativistic compression and heating over a period of seconds. This effect can even cause the stars to collapse to two black holes prior to merger. During the compression phase as much as 10^{53} ergs in neutrinos can be emitted before the stars collapse.[6] This effect may provide a new mechanism to power cosmological gamma-ray bursts and their x-ray and optical counterparts. Here, we report on preliminary efforts to better quantify this release of neutrino energy around the binary and numerically explore its consequences for the development of a $e^+ - e^-$ plasma and associated GRB.

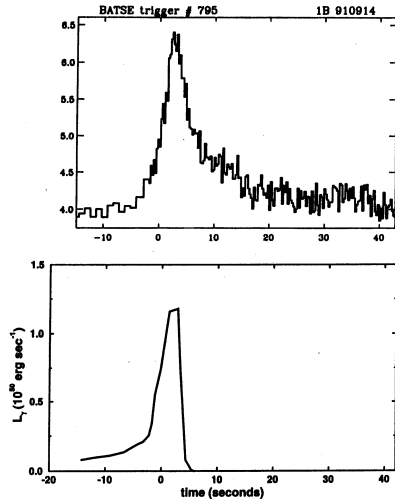In previous work [6] we computed properties of equal-mass neutron star binaries

Figure 1: Calculated gamma-ray burst luminosity (lower curve) compared with a similar single burst from the BATSE catalog. The total released energy from the calculated burst is $\sim 10^{51}$ erg.

as a function of mass and EOS. From these we deduce that compression, heating and collapse can occur at times from a few seconds to a few hours before binary merger. Our calculation of the rates of released binding energy and neutron star cooling suggest that interior temperatures as hot as 70 MeV are possible. This leads to several seconds of high neutrino luminosity, $L_\nu \sim 10^{53}$ erg sec^{-1}. This much neutrino luminosity would convert to an $e^+ - e^-$ pair plasma above the stars as is also observed in supernova simulations.[8] This plasma is a viable candidate source for cosmological gamma-ray bursts.

We have begun to study the transport of this neutrino flux above the neutron star using a modified supernova code.[8] We find entropies as high as $S/k \sim 10^{10}$ (i.e. few baryons) in the pair plasma above the stars. We have also made a preliminary calculation of the hydrodynamic evolution of the pair plasma based upon our calculated neutrino emission and an efficiency (1-10%) for the conversion of neutrinos to $e^+ - e^-$ pairs. The results are quite encouraging. We inject the pair plasma into a spherical grid at a rate consistent with the compression-induced thermal neutrino emission which itself is determined by the gravitational wave emission time.[6] The plasma is evolved hydrodynamically until it becomes optically thin. The calculation is then stopped and the escape of γ-rays is calculated. By this time the average temperature is about 10 eV, but the special relativistic gamma-factor is $\approx 3 \times 10^4$. This produces an integrated photon energy spectrum which is quite typical of observed bursts. It peaks at around 200 keV and extends to a few MeV. Nearly all energy deposited into $e^+ - e^-$ pairs at the star surface ends up as γ rays.

Figure 1 shows a calculation of γ-ray burst luminosity as a function of time

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compared with a typical "single-burst" from the BATSE catalog. The integrated energy in gamma-rays from the calculated burst is $\sim 10^{51}$ erg. The similarity is remarkable considering that there has been no parameter fitting in these calculations. Single-burst durations in the model vary from ~ 1 to 10 sec. We also find that if the masses of the stars differ by more than $\sim 5\%$ that the γ-ray emission separates into two bursts spaced a number of seconds apart. Indeed, there are a number of BATSE bursts indicating this morphology as well. It is not clear, however, how this compression scenario could lead to the typical multiple peak structure observed in many bursts, without recourse to a multiple shock mechanism.

In this regard we note [7] the development of a toroidal fluid vorticity in the neutron star interiors as a lowest stable configuration for the binary. This vorticity is driven by relativistic force terms arising from the motion of the stars with respect to the curved three geometry. Because the circulation driving terms are purely relativistic, they did not appear in previous Newtonian or post-Newtonian calculations. Nevertheless, they aid in the transport of neutrinos from the neutron star interior and help couple the stellar compression to internal heating by producing shocks.

An interesting possible consequence of this toroidal vorticity is that it may lead to the development of extremely strong magnetic fields within the stars. If the field lines are attached to the fluid vorticity, then the shearing of field lines could cause the magnetic fields to grow until magnetic braking becomes important near the equipartition limit, $(H^2/8\pi) = (\rho v^2/2)$. For $\rho \sim 10^{15}$ g cm^{-3} and $v \sim 0.1\ c$. This could imply a magnetic field as large as $H \sim 10^{17}$ gauss.

We have simulated the growth rate of the magnetic field by introducing an electromagnetic vector potential. We followed the evolution of the vector potential for 10 msec (about one orbit) assuming that the fluid is a perfect conductor. The magnetic field energy exponentiated with an e-folding time of about 1 msec. Thus, the field could build up very quickly to a magnitude such that reconnection and back reaction of the fluid inhibits further growth. Due to the high density of fluid kinetic energy in the vorticities, the limiting fields could approach the equipartition limit. As the field grows it should bubble from the surface (W. Kluzniak, Priv. Comm.). Interactions of the bubbling field with the surface pair plasma might lead to the multiple peak structure observed in many GRB's.

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